Cost and Benefits of Denser Topologies for the Smart Grid

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Abstract The Smart Grid promises to reshape how electricity is generated, distributed, and used. More delocalized generation based on renewable sources will transform end-users into prosumers (producers and consumers) of energy. These will require electric and supporting ICT infrastructures to be able to openly access the energy market. In this paper, we focus on the electric infrastructure issue related to the Smart Grid topic. We consider network models from the literature of Complex Network Analysis and evaluate their ability to be used for the Distribution Grid to reduce the cost of electricity distribution based on topological property. Our initial conclusion is that denser topologies are helpful to reach the goal. However, the cost of realizing such topologies in terms of cabling is not negligible, as we show.

1 Introduction

The Power Grid has been designed over the years as a hierarchical mono-directional infrastructure with large generation facilities and distribution infrastructure that reaches the end-users. In recent decades, however, unbundling tendencies have begun to change the energy market. Unbundling in the electricity sector proposes to add more players to the market as producers, sellers, or distributors of energy. The goal is to promote competition and innovation in the sector together with better tariffs and services for the consumer [11]. In addition, the availability of affordable small-scale generation facilities (e.g., photovoltaic panels and small wind turbines) shifts

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the generation towards the periphery of the infrastructure [13]. Such trends combined lead to the emergence of a new figure in the energy panorama: the *prosumer*. This term characterizes the new actors, who are both producers and consumers of energy, operating in this scenario. They are increasing in number, and will most likely demand a market with total freedom for energy trading.

With generation moving massively to a local scale, the Power Grid will require an update to evolve into a more efficient and information-driven system, a fact that we take as a defining characteristic of the Smart Grid to come. In particular, the Medium and Low Voltage layers of the Grid are likely to be affected by the energy produced and consumed by prosumers. Therefore, we predict that the current Medium and Low Voltage Grid will be an enabler or a repressor for the transition to an electricity system mainly based on prosumers. The Grid and its electricity distribution cost will determine the success of energy exchanges at the local level.

Based on our previous analysis of the topology of the Dutch Grid and the identification of a relationship between costs for electricity distribution and topology [16], in this paper we take a closer look at the cost and benefits of realizing the Medium and Low Voltage Grid with denser type of network (i.e., a network with an increased number of connections) compared to the current infrastructure. We place particular emphasis on assessing the cost of the current Medium and Low Voltage Grid based on actual cable pricing information. To evaluate the benefits of networks denser than the current one, we use statistical topological metrics that are associated with electricity distribution costs.

The paper is organized as follows. In Sect. 2, we introduce Complex Network Analysis (CNA), our main tool for topological investigation and the principles followed in designing denser networks. Section 3 focuses on the costs of realizing denser electrical Grids and the accompanying benefits. The main related work of the literature is summarized in Sect. 4. The conclusion of the paper is provided in Sect. 5.

2 Complex Network Analysis and the Power Grid

Complex Network Analysis is a branch of Graph Theory taking its root in the early studies of Erdős and Rényi [7] on random graphs and considering statistical structural properties of very large graphs. The first systematic studies appeared in the late 1990s, e.g. [3, 21], having the goal of looking at the properties of large networks with complex systems behavior. Since then, Complex Network Analysis has been used in many diverse fields of knowledge, from biology to chemistry, from linguistics to social sciences, from computer networks and the web to virus spreading, to logistics and also inter-banking systems [2]. Man-made infrastructures are especially interesting to study under the Complex Network Analysis lenses, especially when they are large-scale and grow in a decentralized and independent fashion, thus not being the result of a global design, but rather of many local autonomous designs.

CNA techniques that have been applied to the Power Grid, mainly focused on the reliability of the High Voltage Grid. The studies appeared after blackouts of important electricity infrastructures (e.g., U.S. Grid and Italian Grid), it is thus not surprising they mainly focused on reliability issues [1, 4, 5].

In our own previous study [16], we analyzed the Dutch Medium and Low Voltage Grid. The main findings are as follows: first, the network samples show a small average connectivity (average node degree $\langle k \rangle = 2.009$ for the Low Voltage and $\langle k \rangle = 2.129$ for the Medium Voltage); second, it is possible to roughly categorize the networks based on the number of nodes; and third, there is no clear evidence of a specific topological structure belonging to a well-known model in the 24 samples analyzed. This last point refers to the absence of characteristics that possess other complex networks from biology or technology, such as Scale-Free or Small-World properties. In our follow-up study [17], we considered network models that have proven successful in showing salient characteristics of technological networks and we analyzed possible topological evolutions of the current Grid to see which topology is best suited for supporting local-scale energy exchange. For each model, we considered three values of increasing average node degree ($\langle k \rangle = 2$, $\langle k \rangle = 4$, and $\langle k \rangle = 6$) to study the effects of increasing connectivity on the performance of the network. As a general result, we see that just considering the topology provides benefits to the efficiency of the network in fundamental aspects such as characteristic path length, clustering coefficient, and network reliability against disruption. Naturally, creating denser topologies for a physical infrastructure translates into higher cable deployment costs.

3 Economic Considerations

Traditionally, the problem of evaluating the expansion of an electrical system is a complex task that involves both the use of modeling, usually based on operation research optimization techniques and linear programming [8], as well the experience and vision of experts. However, with more distributed generating facilities at local scale, traditional methods have limits and need to be modified or updated to take into account the new scenario the Smart Grid brings into play. The models that we have analyzed in [17] also need to be evaluated from the economic point of view. How much will it cost to build electrical infrastructures according to these models? What is the actual cost of adding a physical edge to the topology?

One important difference between a physical infrastructure such as the Power Grid and the WWW or social networks is the physical presence of cables that connect the Medium Voltage substations or Low Voltage end-users' generating units. While establishing a link from a Web page to another one is free, each increase in connectivity in the Power Grid implies costs in order to build or adapt the substation or end-user premise involved, as well as costs for the cables required for the connection. To assess these costs in the Medium and Low Voltage infrastructure,

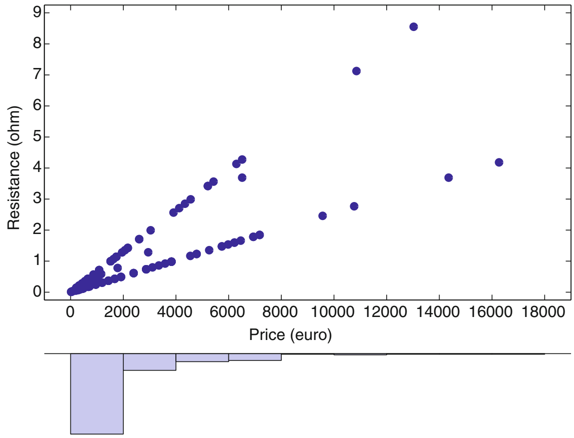

Fig. 1 Price-resistance pairs joint plot

we consider a simple relation where the cost of cabling and cost of substations are added:

$$C_{impl} = \sum_{j=1}^{N} Ssc_j + \sum_{i=1}^{M} Cc_i \tag{1}$$

where C_{impl} stands for cost for implementation, Ssc_j is the adaptation cost for the substation j and Cc_i is the cost for the cable i. The cost of the cable can be expressed as a linear function of the distance the cable i covers: $Cc_i = C_{uc_i} \cdot l_i$, where C_{uc_i} is the cable cost per unit of length and l_i is the length of the cable. There are several types of cables used for power transmission and distribution with varying physical characteristics and costs. In addition, the cost for installation can vary significantly [14]. In the present work, to provide an initial estimate, we simply consider cabling costs and ignore substation ones. While the former are directly tied to the topology and length of the links, the latter pricing is too dependent on other factors (e.g., different equipment in the substation). As a source of data for cable type and pricing, we have been provided (courtesy of Enexis B.V. the Netherlands) with cable characteristics and prices, together with topological information, for 11 network samples belonging to the Low Voltage network and 13 samples belonging to the Medium Voltage network of the Northern Netherlands.

The length of the cables plays an important role for both total resistance (therefore losses) and price. If one considers the correlation between the price and resistance, high values are found using Spearman's rank correlation coefficient, shown in Table 24 in [17]. For generating synthetic networks it is especially important to obtain values for both the properties of cables that are similar to the ones used in practice. A plot of the two variables characterizing each cable reveals that the majority of the samples concentrate in the lower tails of the joint distribution. Figure 1 shows the relation between the price and resistance where the values concentrate in the lower corner of $price \times resistance$. In the chart in Fig. 1, two distinct lines deviate

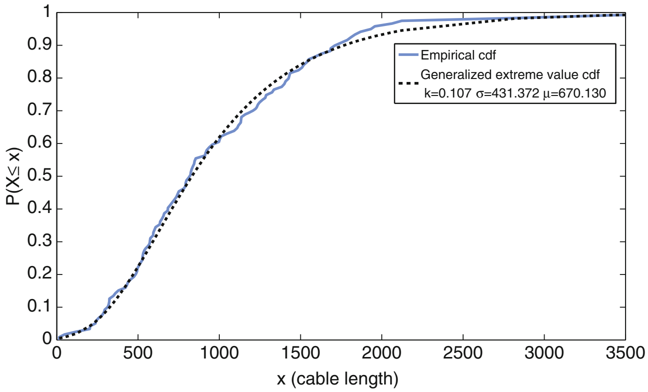

Fig. 2 Cumulative distribution function for cable length for cable type "3x1x70al" in Northern Netherlands medium voltage

from the lower left corner. They represent the two main types of cables to be used in that sample of the Low Voltage network to cover different distances and result in increasing price and resistance for longer lines. The problem of extracting cable properties can be, however, approached in another way: *evaluate for each type of cable (i.e., physical property and technology) used in a certain category of sample belonging to the Medium or Low Voltage network (Small, Medium and Large based on the number of nodes* [17]), *how the lengths of the cables used are distributed.* In fact, given a certain type of cable and its length, all other relevant properties for our analysis are then available (i.e., cable total resistance, total cost and supported current).

When fitting the distribution of lengths to cable types belonging to Low Voltage and Medium Voltage, one notes a rapid decay in the probability distribution, with the majority of lengths for the Low Voltage cable types on the order of tens of meters, and Medium Voltage cables in the hundreds of meters. Fitting the length to a statistical probability distribution gives a good approximation for the Low Voltage cable lengths as exponential distributions $\left(y = f_X(x;\mu) = \frac{1}{\mu} e^{\frac{-x}{\mu}}\right)$, while for Medium Voltage cable lengths, the generalized extreme value distribution fits best $\left(y = f_X(x;k,\mu,\sigma) = \frac{1}{\sigma}\left(1 + k\frac{x-\mu}{\sigma}\right)^{-1-\frac{1}{k}} \exp\left\{-(1 + k\frac{x-\mu}{\sigma})^{-\frac{1}{k}}\right\}\right)$; these hypotheses are supported by the Kolmogorov-Smirnov test results. An example is shown in Fig. 2.

Assume that, statistically speaking, the distribution of the lengths for each type of cable in the synthetic networks is the same as in the physical samples. Therefore, once we know the probability of using a certain type of cable i ($p_{cable_i} = \frac{\#cable_i}{\sum_k \#cable_k}$ where $\#cable_i$ is the number of occurrences of cable type i in a certain network sample) that has a certain cost and resistance per meter and a specific current supported, we can estimate the cables that are used in the synthetic samples together with their properties.

Table 1 Cabling cost for $\langle k \rangle \approx 2$ synthetic samples

Sample type	Size	Cost (thousand euro)
Low voltage—small	≈20	≈30
Low voltage—medium	≈90	≈78
Low voltage—large	≈200	≈449
Medium voltage—small	≈250	≈32000
Medium voltage—medium	≈500	≈42000
Medium voltage—large	≈1000	≈43000

Given the information about cable prices, it is possible to estimate the cost for realizing a network with a certain connectivity and to determine whether such networks are able to lower the (economic) barrier towards decentralized energy trading. The results for Low Voltage and Medium Voltage networks for *Small*, *Medium* and *Large* types with an average node degree $\langle k \rangle \approx 2$ are shown in Table 1. The results for $\langle k \rangle \approx 4$ and $\langle k \rangle \approx 6$ are about two and three times more expensive since there is an increase in the number of edges by the same quantity. The small difference in costs between the *Medium* and *Large* types of networks for Medium Voltage is related mainly to the different technologies of cable types that are used for these types of networks.

The cost in realizing infrastructures with more connectivity compared to the current infrastructures is not the only aspect of comparison. It is essential to show how this additional connectivity provides benefits in the form of a decrease of the costs of electricity distribution. In our previous work [16] we defined two sets of metrics (α and β) to assess the topological aspects that influence the cost of electricity. In particular, α considers the aspects that are related to losses in the network, while β deals with reliability and capacity properties of the network. In order to compare on the same basis (i.e., considering α and β metrics) the physical samples of the Northern Netherlands and generated networks, it is essential to associate to the generated networks realistic physical properties such as resistance and supported current. These properties can be extracted from each physical sample (i.e., Medium or Low Voltage and its *Small*, *Medium* or *Large* category) and associated to the corresponding generated synthetic samples. This mapping can be done with the assumption that, statistically, the properties of cables in the new networks (i.e., synthetic) will remain the same as in the current networks (i.e., physical samples). To enable this mapping the statistical analysis of the physical samples shown above is the necessary tool.

The comparison for the electricity cost based on the topological parameters for Low Voltage networks is shown in Fig. 3. Red dots in the $\alpha \times \beta$ plane represent the Northern Netherlands samples while the white diamonds represent the generated Small-World networks. Small-World has been chosen for the comparison since it is the network model that scores best in the pure topological comparison [17]. One sees that when the connectivity is sufficiently high (i.e., $\langle k \rangle \approx 4$), the synthetic samples score better than the physical ones. On average for the α metric, the improvement is about 50 % compared to the Netherlands samples, while about 60 % when the connectivity is increased to $\langle k \rangle \approx 6$. Considering the β metric, the improvement are

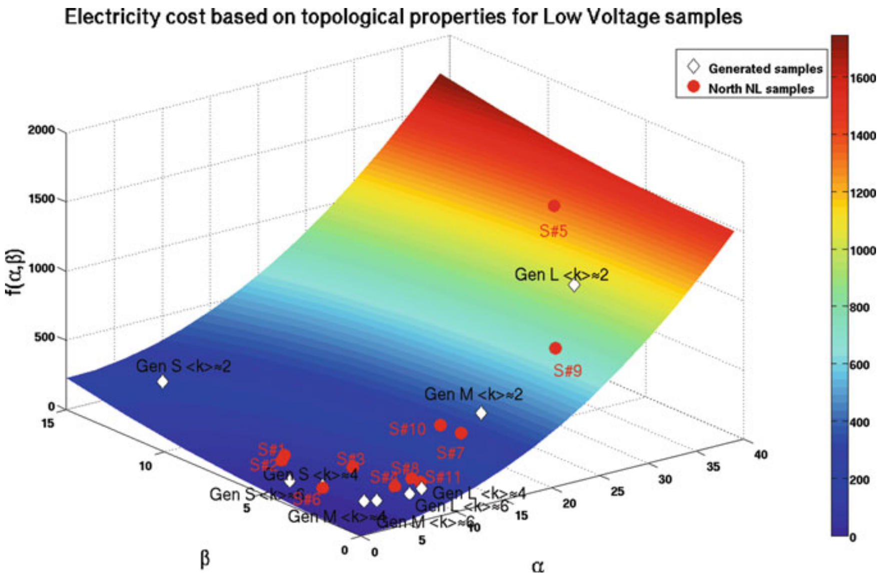

Fig. 3 Comparison of the transport cost between synthetic and real low voltage grids

30 and 40 % for the $\langle k \rangle \approx 4$ and $\langle k \rangle \approx 6$ situations, respectively. Similar considerations apply to the Medium Voltage samples with improvements that reach up to 60 % compared to the physical samples when higher connectivity is added ($\langle k \rangle \approx 6$).

4 Related Work

CNA for network growth and evolution is mainly used in the field of physics, considering man-made or natural networks [6] or social networks [12]. The Internet has also been the subject of investigation in its topological evolution [19]. The main aim of these works is to present and describe the evolution of such networks, rather than offering a design tool for the infrastructure. Approaches that apply CNA to the Power Grid essentially investigate the current Grids analyzing their topological properties. Most of the work focuses on either considering the membership of a network in a certain category or on evaluating the reliability and tolerance to failures of the network [15]. Only very few studies consider the improvement of Power Grids taking into account the addition of few power lines and their topological benefit [10, 18]. Wang et al. [20] applied Complex Network Analysis to analyze the Smart Grid mainly to understand the communication infrastructure and network topologies needed to support decentralized control. However, these publications consider once again only the High Voltage Grids. In practice, electrical engineers consider several aspects: economics, environment, feasibility, and concurrent safety [9]. Taking into consideration all these aspects makes the task of planning a complex decision problem with multiple objectives.

5 Concluding Remarks

The Smart Grid promises a new approach to energy generation and distribution where the Medium and Low Voltage Grid will change role and importance. In fact, the topology of the network plays an important role, in influencing the costs of electricity distribution. We have proposed network models from the literature of Complex Network Analysis and investigated how topologies with increased connectivity (i.e., higher node degree) could be beneficial in lowering those parameters that influence the price of distributing electricity. On the other hand, we note an the increase in costs for denser topologies. Our approach does replace the current planning techniques used by energy distributors, but it aims at being a decision support tool in evaluating new strategies for the future energy panorama.

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